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A conical mandrel tube drawing test designed to assess failure criteria

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ABSTRACT

Cold tube drawing is a metal forming process which enables to produce tubes with high dimensional precision. It consists in reducing tube dimensions by pulling it through a die. Tube outer diameter is calibrated by a die and the tube inner diameter and thickness are calibrated by a mandrel. One of the major concern of metal forming industry is the constant improvement of productivity and product quality. In the aim of pushing the process to the limit the question is how far the material can be processed without occurrence of failure. In the present study, a long conical mandrel with a small cone angle was designed in order to carry out drawing tests up to fracture with experimental conditions very close to the industrial process. The FEM of the process was built in order to access the local stress and strain data. A specific emphasis was put on the friction characterisation. For that purpose force measurement during the conical mandrel experiments enabled to characterise a pressure dependent friction coefficient constitutive law by means of an inverse analysis. Finally, eleven failure criteria were selected to study the drawability of cobalt–chromium alloy tubes. The assessment of failure criteria based on damage variables or damage accumulation variables involved their calibration on uniaxial tensile tests. The experimental studies were completed by SEM fractography which enabled to understand the fracture locus and the propagation direction of the fracture.

1. Introduction

There is a growing concern in the metal forming industry to improve the quality of the produced parts while reducing manufacturing time and production costs. Process optimisation requires trials and errors which are time and money consuming. The current development of finite element modelling (FEM) allows to improve the understanding of the process by accessing history of stress and strain distributions in the formed part. Thus, FEM combined with specific designed tests is a tool for process optimisation.

This study focuses on the cold tube drawing process which is widely used to manufacture tubes for biomedical applications (Poncin et al., 2004; Fang et al., 2013; Hanada et al., 2013). Such tubes are required to have precise dimensions and a good surface finish that cannot be obtained with the extrusion process. The principle of cold drawing is to reduce tube cross section and wall thickness by pulling a tube through a die. Tube outer diameter is calibrated by the die diameter. In the particular case of mandrel drawing, a rod is inserted inside the tube in order to calibrate the inner diameter. The process is performed at room temperature. The end product is the result of a series of drawing passes in order to progressively reduce inner and outer diameters. Each pass is defined in such a way that the tube is plastically deformed and the fracture is prevented. The growing concern of reducing production time and cost requires each pass to be optimized. Thus imposed plastic deformation has to get closer to the fracture limit. Consequently, process optimization involves failure prediction.

In this study a conical mandrel drawing test was designed in order to calibrate and evaluate ductile failure criteria. The interest of such a test is to calibrate criteria for realistic stress and strain states regarding the tube drawing process. It consists in a long conical mandrel designed to perform tube drawing from zero thickness reduction up to a maximum thickness and section reduction leading to fracture. The failure is characterized by means of failure criteria that are computed by FEM.

This paper begins with a presentation of the methods that are generally used for failure studies. The emphasis is put on the interest of failure criteria. Then, eleven failure criteria which are of interest are presented. A second part details the design of the mandrel and the experimental procedure of the drawing on the conical mandrel. Then the presentation of the experimental results are followed by the development of the methodology to compute the failure criteria. This part deals with the FEM of the conical mandrel drawing with a specific emphasis on the contact and friction characterization. Besides, the calibration of the failure criteria and the

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characterization of the material constitutive behaviour by means of tensile tests is presented. Finally, a comparative study of the predicted section reductions at failure is made relative to experimental observations to evaluate criteria predictability.

2. Failure prediction

2.1. Introduction

In the literature, there are four reported methods to study ductile fracture: continuous damage mechanics models (Lemaitre, 1985; Chaboche, 1988), porous solid mechanics models (Gurson, 1977; Tvergaard and Needleman, 1984), cohesive models (Barenblatt, 1962) and phenomenological models. The latter do not directly model physical mechanisms of ductile fracture but predict its occurrence. In industrial forming processes the main issue is to predict failure initiation in order to avoid fracture. The point is not to understand failure mechanism but to have an effective failure indicator. As a consequence, the study of crack propagation and the development of mechanical analysis of ductile cracking is not relevant in this study. Moreover, the implementation in FEM of complex physically based models such as continuous damage mechanics models, porous solid mechanics models or cohesive models is computationally much more time expensive than phenomenological models (Zadpoor et al., 2009). Vallellano et al. (2008) and Takuda et al. (1999) found failure criteria to be good competitors compared to physically based models. They used different failure criteria to predict fracture limits of aluminum 2024-T3 and found the same limits as Lee et al. (1997) and Tang et al. (1999) who used a continuum ductile failure criterion. For these reasons, the emphasis of this study is put on finding criteria for predicting fracture loci and deformation levels at the onset of fracture.

Historically, several failure criteria have been established. They describe the failure in terms of mechanical variables such as stress, strain or mechanical work. In all models presented in this work failure criteria are based on functions which depend on these variables. If these functions reach a critical value, failure is expected. There are two simple models for failure prediction. The first one is to consider that failure occurs when a function of the current stress tensor reaches a critical value. The second model is to consider a function of current strain tensor. Both of these models are based on instantaneous damage variable D. Their general expressions are the following:

$$D = f(\underline{\underline{\sigma}}) \quad or \quad D = f(\underline{\underline{\epsilon}}^p) \tag{1}$$

where $\underline{\underline{\sigma}}$ and $\underline{\underline{\epsilon}}^p$ are the current Cauchy stress and the plastic strain tensors respectively.

Additionally, there are more complex failure criteria which consider mechanical work. These criteria take into account the stress and strain history. They are based on a damage accumulation variable D whose general expression is detailed below:

$$D = \int_0^{\bar{\epsilon}_p} f(\underline{\underline{\sigma}}) d\bar{\epsilon}_p \tag{2}$$

with $d\bar{\epsilon}_p$ the equivalent plastic strain increment and $\bar{\epsilon}_p$ the current equivalent plastic strain.

Freudenthal (1950) was the first to establish a failure criterion introducing the work of plastic deformation. Cockcroft and Latham (1968) successively suggested that the largest principal stress was more likely to cause fracture and they established a failure criterion based on the highest tensile stress. Brozzo et al. (1972) introduced the level of hydrostatic stress in a new failure criterion in accordance with the study of Bridgman (1952) who showed that imposing hydrostatic pressures could contain the growth of cavities and improve formability. Their conclusions were reinforced recently by Wu et al. (2009). McClintock (1968), Rice and Tracey (1969) and Oyane et al. (1980) established other failure criteria according to the void growth model and the theory of porous media. In a general way, the onset of failure is predicted when the ratio of the damage variable (1) or the damage accumulation variable (2) to a limit value reaches 1:

$$\frac{D}{D^{\text{crit}}} \geq 1 \tag{3}$$

The critical value D^{crit} for each criterion is calibrated on mechanical tests like tensile tests or upsetting tests for example.

2.2. Presentation of eleven failure criteria

Many researchers have worked on failure criteria and they have suggested different phenomenological expressions of the instantaneous damage or damage accumulation variables. Among all the failure criteria available a limited number of criteria is selected for the purpose of this study. Only criteria that can be calibrated on a single experimental test (i.e. uniaxial tensile test) are chosen. Thus, eleven failure criteria are considered. They are listed in Table 1. In the table D_i $(i = 1, \ldots, 11)$ are the damage variable or damage accumulation variable, σ_j $(\sigma_1 > \sigma_2 > \sigma_3)$ are the three principal stresses, τ_{max} is the maximum shear stress, $\bar{\sigma}$ is the Mises equivalent stress and σ_m is the hydrostatic stress.

3. The conical mandrel tube drawing test

The first method to determine tube drawing limit is to perform a series of drawing tests with several mandrels of different diameters. The drawing limit is reached when the use of a mandrel makes the drawing impossible. This approach has mainly two drawbacks: it is time consuming due to the number of necessary

Table 1
Details of the selected fracture criteria.

Type	Abbreviation	Criterion	Damage or damage accumulation variable
1	STRN	Equivalent strain	$D_1 = \bar{\epsilon}$
1	MSS	Maximum shear stress	$D_2 = \tau_{\text{max}} = \frac{\sigma_1 - \sigma_3}{2}$
1	SHAB	Vujovic and Shabaic (1986)	$D_3 = \frac{3\sigma_m}{\bar{\sigma}}$
2	FREU	Freudenthal (1950)	$D_4 = \int_0^{\bar{\epsilon}_p} \bar{\sigma} d\bar{\epsilon}_p$
2	COCK	Cockcroft and Latham (1968)	$D_5 = \int_0^{\bar{\epsilon}_p} \max(0, \sigma_1) d\bar{\epsilon}_p$
2	RICE	Rice and Tracey (1969)	$D_6 = \int_0^{\bar{\epsilon}_p} \exp\left(\frac{3\sigma_m}{2\bar{\sigma}}\right) d\bar{\epsilon}_p$
2	BROZ	Brozzo et al. (1972)	$D_7 = \int_0^{\bar{\epsilon}_p} \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} d\bar{\epsilon}_p$
2	ARGO	Argon et al. (1975)	$D_8 = \int_0^{\bar{\epsilon}_p} (\sigma_m + \bar{\sigma}) d\bar{\epsilon}_p$
2	OH	Oh et al. (1976)	$D_9 = \int_0^{\bar{\epsilon}_p} \frac{\sigma_1}{\bar{\sigma}} d\bar{\epsilon}_p$
2	AYAD	Ayada et al. (1984)	$D_{10} = \int_0^{\bar{\epsilon}_p} \frac{\sigma_m}{\bar{\sigma}} d\bar{\epsilon}_p$
2	TREN	Tresca energy	$D_{11} = \int_0^{\bar{\epsilon}_p} \frac{(\sigma_1 - \sigma_3)}{2} d\bar{\epsilon}_p$